US009076827B2

(12) **United States Patent**
Bour et al.

(10) **Patent No.: US 9,076,827 B2**
(45) **Date of Patent: Jul. 7, 2015**

(54) **TRANSFER CHAMBER METROLOGY FOR IMPROVED DEVICE YIELD**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 900 days.

(21) Appl. No.: **13/230,573**

(22) Filed: **Sep. 12, 2011**

(65) **Prior Publication Data**

US 2012/0118224 A1 May 17, 2012

Related U.S. Application Data

(60) Provisional application No. 61/382,835, filed on Sep. 14, 2010.

(51) **Int. Cl.**
C30B 25/16 (2006.01)
C30B 25/08 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H01L 21/67196*** (2013.01); *Y10T 117/10* (2015.01); *Y10T 117/1008* (2015.01);
(Continued)

(58) **Field of Classification Search**
CPC H01L 21/67196; H01L 21/67248; H01L 22/12; H01L 21/0242; H01L 21/02458; H01L 21/02507; H01L 21/0254; H01L 22/26; H01L 33/007; Y10T 117/10; Y10T 117/1004; Y10T 114/1008; C30B 35/00; G01K 11/20; G01K 2217/00
USPC 117/201, 86, 85; 118/708, 712, 696, 118/697
See application file for complete search history.

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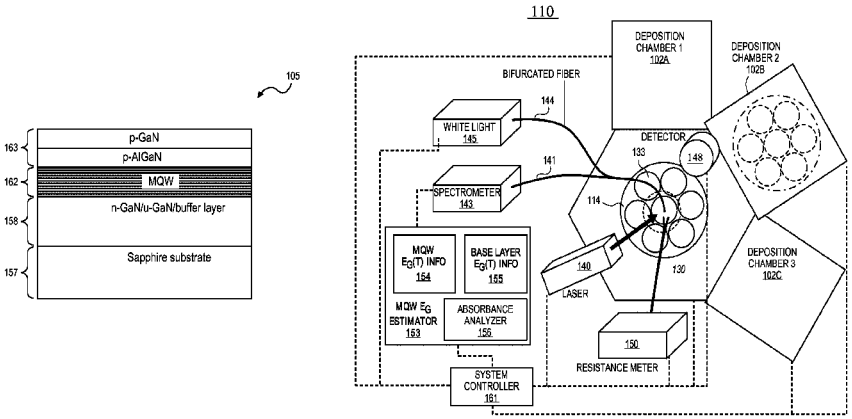
(57) **ABSTRACT**

Apparatus and method for control of epitaxial growth parameters, for example during manufacture of light emitting diodes (LEDs). Embodiments include PL measurement of a group III-V film following growth while a substrate at an elevated temperature is in a transfer chamber of a multi-chamber cluster tool. In other embodiments, a film thickness measurement, a contactless resistivity measurement, and a particle and/or roughness measure is performed while the substrate is disposed in the transfer chamber. One or more of the measurements performed in the transfer chamber are temperature corrected to room temperature by estimating the elevated temperature based on emission from a GaN base layer disposed below the group III-V film. In other embodiments, temperature correction is based on an absorbance band edge of the GaN base layer determined from collected white light reflectance spectra. Temperature corrected metrology is then used to control growth processes.

15 Claims, 10 Drawing Sheets



(51) **Int. Cl.**

C30B 25/10	(2006.01)
C23C 16/06	(2006.01)
C23C 16/52	(2006.01)
H01L 21/67	(2006.01)
G01K 11/20	(2006.01)
H01L 21/66	(2006.01)
H01L 21/02	(2006.01)
H01L 33/00	(2010.01)

(52) **U.S. Cl.**

CPC *Y10T117/1004* (2015.01); ***G01K 11/20*** (2013.01); *G01K 2217/00* (2013.01); *H01L 21/0242* (2013.01); *H01L 21/02458* (2013.01); *H01L 21/02507* (2013.01); *H01L 21/0254* (2013.01); ***H01L 21/67248*** (2013.01); ***H01L 22/12*** (2013.01); *H01L 22/26* (2013.01); *H01L 33/007* (2013.01)

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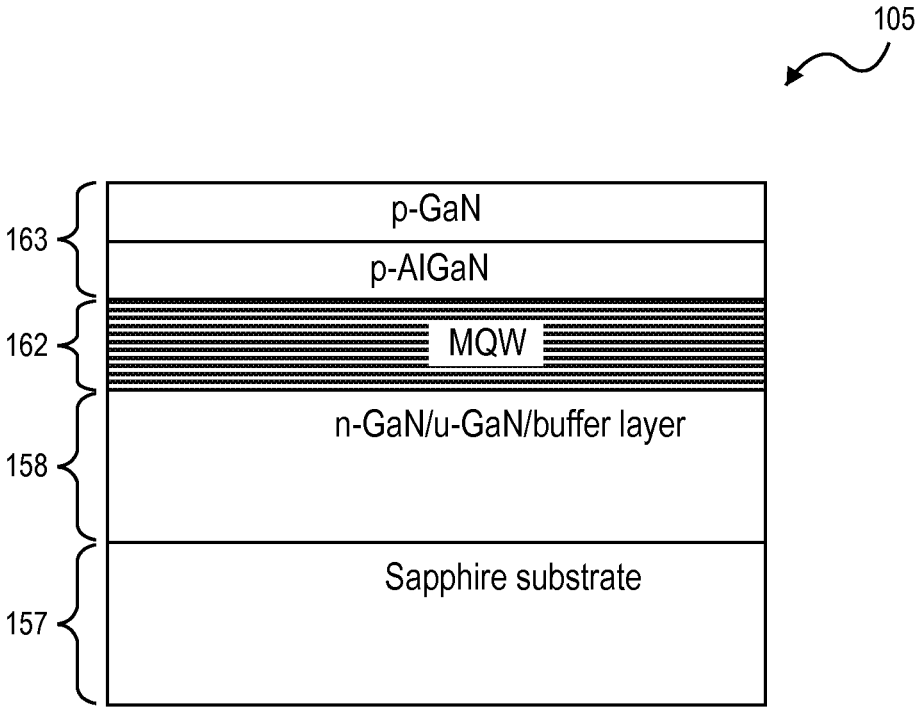
105
163
p-GaN
p-AlGaN
162
MQW
158
n-GaN/u-GaN/buffer layer
157
Sapphire substrate

FIG. 1A

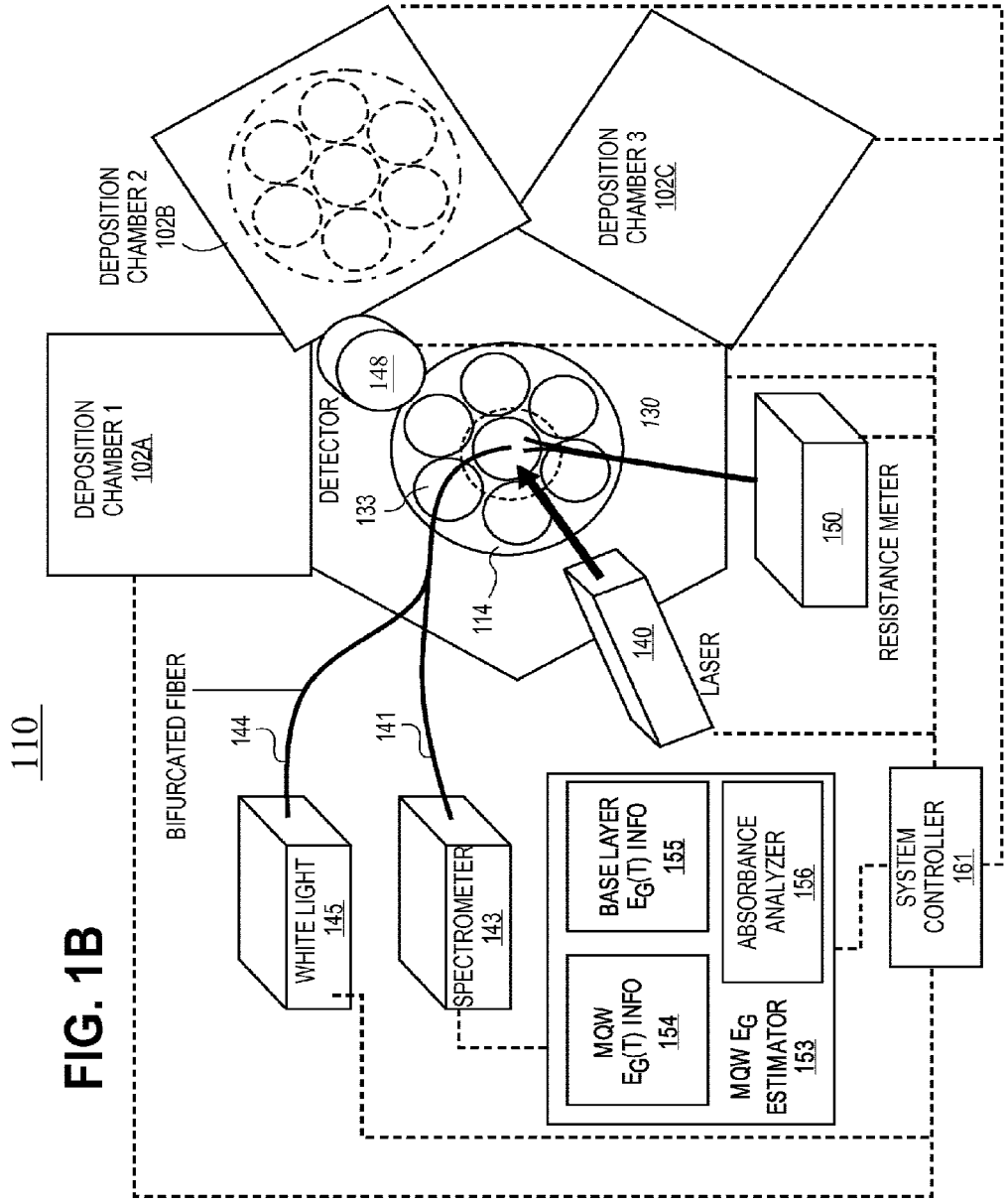
110
DEPOSITION CHAMBER 1 102A
DEPOSITION CHAMBER 2 102B
DEPOSITION CHAMBER 3 102C
DETECTOR
133
148
130
114
140
LASER
150
RESISTANCE METER
BIFURCATED FIBER
144
141
WHITE LIGHT 145
SPECTROMETER 143
MQW E_G(T) INFO 154
BASE LAYER E_G(T) INFO 155
ABSORBANCE ANALYZER 156
MQW E_G ESTIMATOR 153
SYSTEM CONTROLLER 161

FIG. 1B

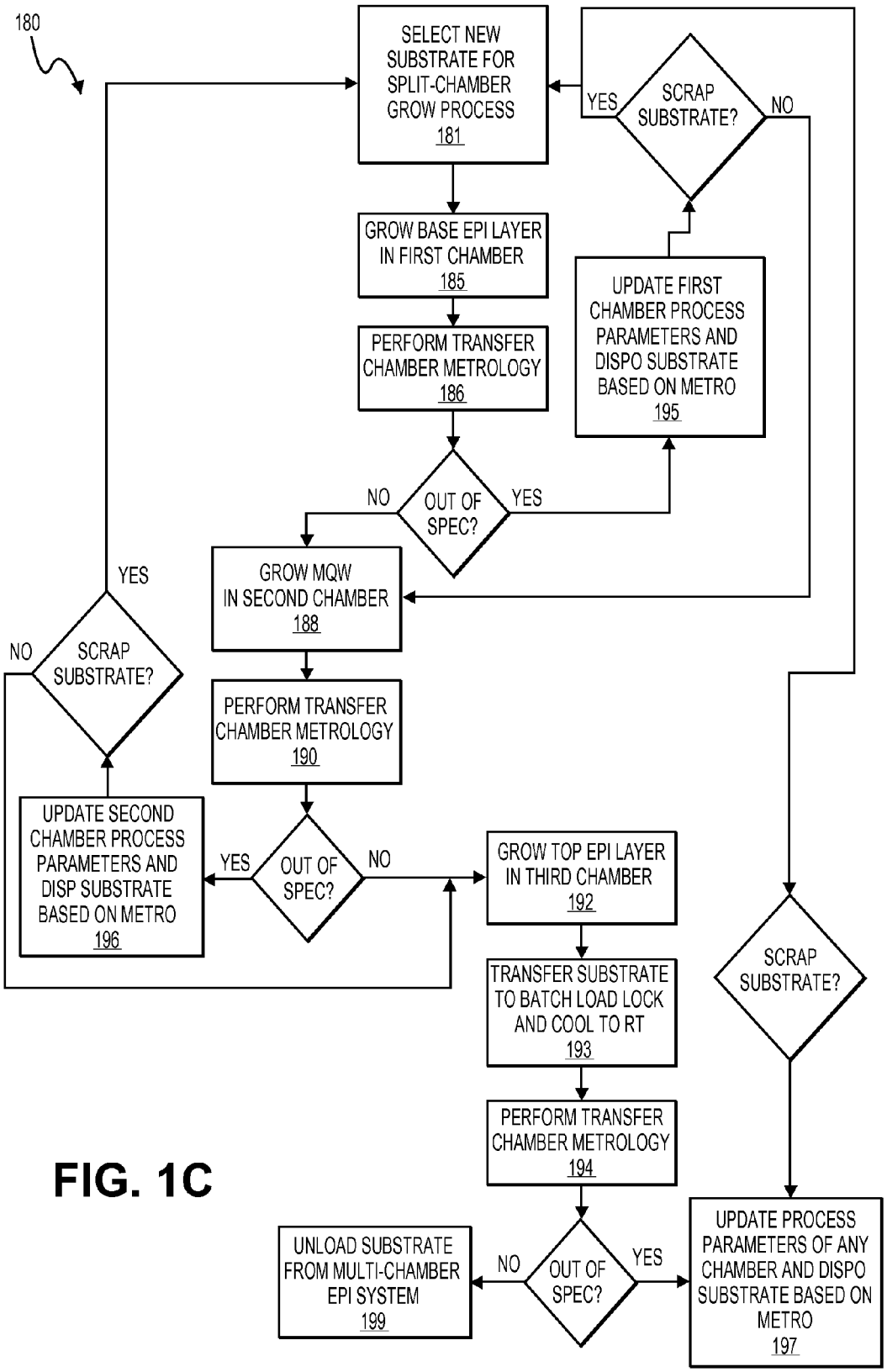
180
SELECT NEW SUBSTRATE FOR SPLIT-CHAMBER GROW PROCESS 181
SCRAP SUBSTRATE?
YES
NO
GROW BASE EPI LAYER IN FIRST CHAMBER 185
PERFORM TRANSFER CHAMBER METROLOGY 186
UPDATE FIRST CHAMBER PROCESS PARAMETERS AND DISPO SUBSTRATE BASED ON METRO 195
OUT OF SPEC?
NO
YES
GROW MQW IN SECOND CHAMBER 188
PERFORM TRANSFER CHAMBER METROLOGY 190
SCRAP SUBSTRATE?
YES
NO
UPDATE SECOND CHAMBER PROCESS PARAMETERS AND DISP SUBSTRATE BASED ON METRO 196
OUT OF SPEC?
YES
NO
GROW TOP EPI LAYER IN THIRD CHAMBER 192
TRANSFER SUBSTRATE TO BATCH LOAD LOCK AND COOL TO RT 193
PERFORM TRANSFER CHAMBER METROLOGY 194
SCRAP SUBSTRATE?
OUT OF SPEC?
NO
YES
UNLOAD SUBSTRATE FROM MULTI-CHAMBER EPI SYSTEM 199
UPDATE PROCESS PARAMETERS OF ANY CHAMBER AND DISPO SUBSTRATE BASED ON METRO 197

FIG. 1C

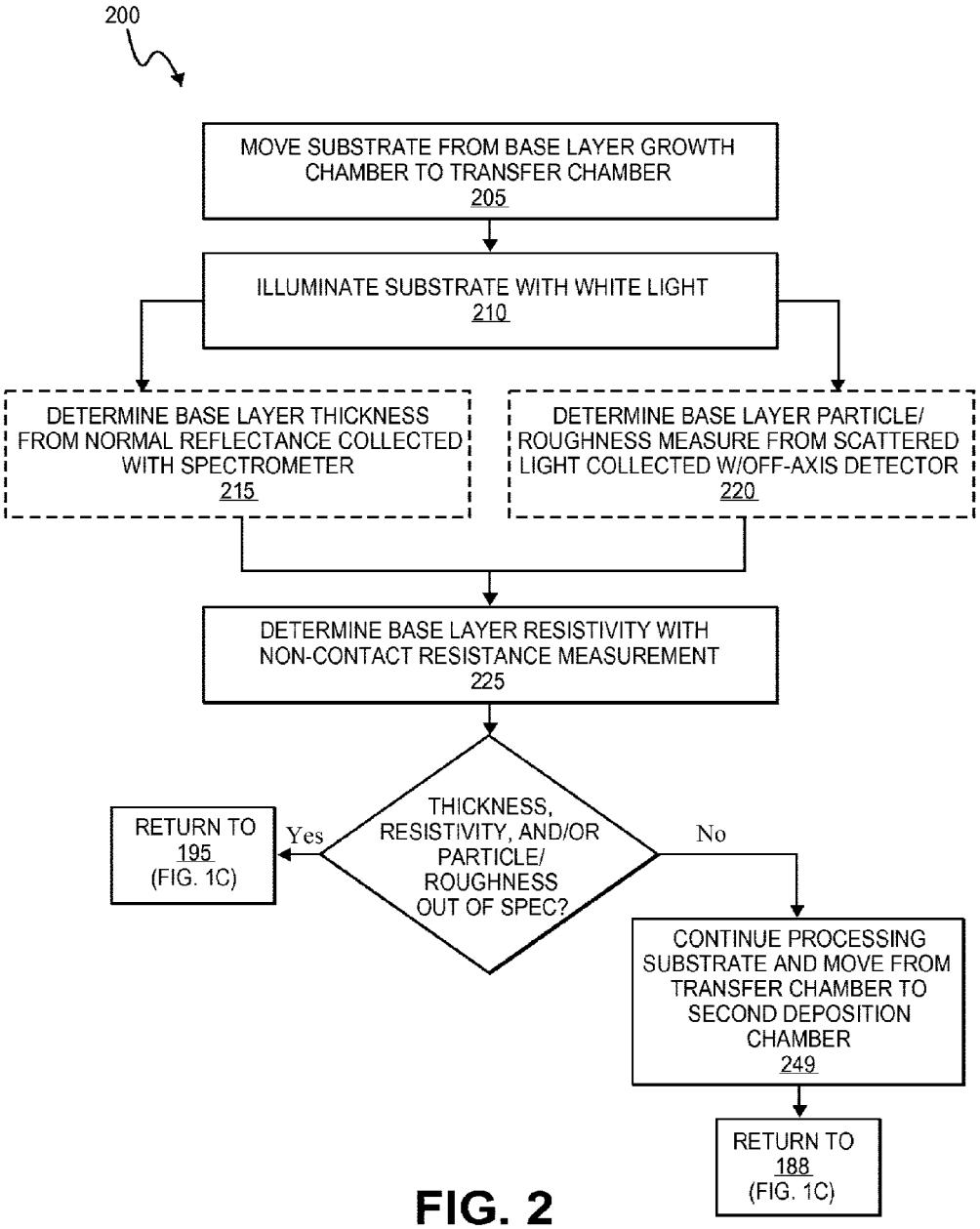
200
MOVE SUBSTRATE FROM BASE LAYER GROWTH CHAMBER TO TRANSFER CHAMBER
205
ILLUMINATE SUBSTRATE WITH WHITE LIGHT
210
DETERMINE BASE LAYER THICKNESS FROM NORMAL REFLECTANCE COLLECTED WITH SPECTROMETER
215
DETERMINE BASE LAYER PARTICLE/ ROUGHNESS MEASURE FROM SCATTERED LIGHT COLLECTED W/OFF-AXIS DETECTOR
220
DETERMINE BASE LAYER RESISTIVITY WITH NON-CONTACT RESISTANCE MEASUREMENT
225
THICKNESS, RESISTIVITY, AND/OR PARTICLE/ ROUGHNESS OUT OF SPEC?
Yes
RETURN TO 195 (FIG. 1C)
No
CONTINUE PROCESSING SUBSTRATE AND MOVE FROM TRANSFER CHAMBER TO SECOND DEPOSITION CHAMBER
249
RETURN TO 188 (FIG. 1C)

FIG. 2

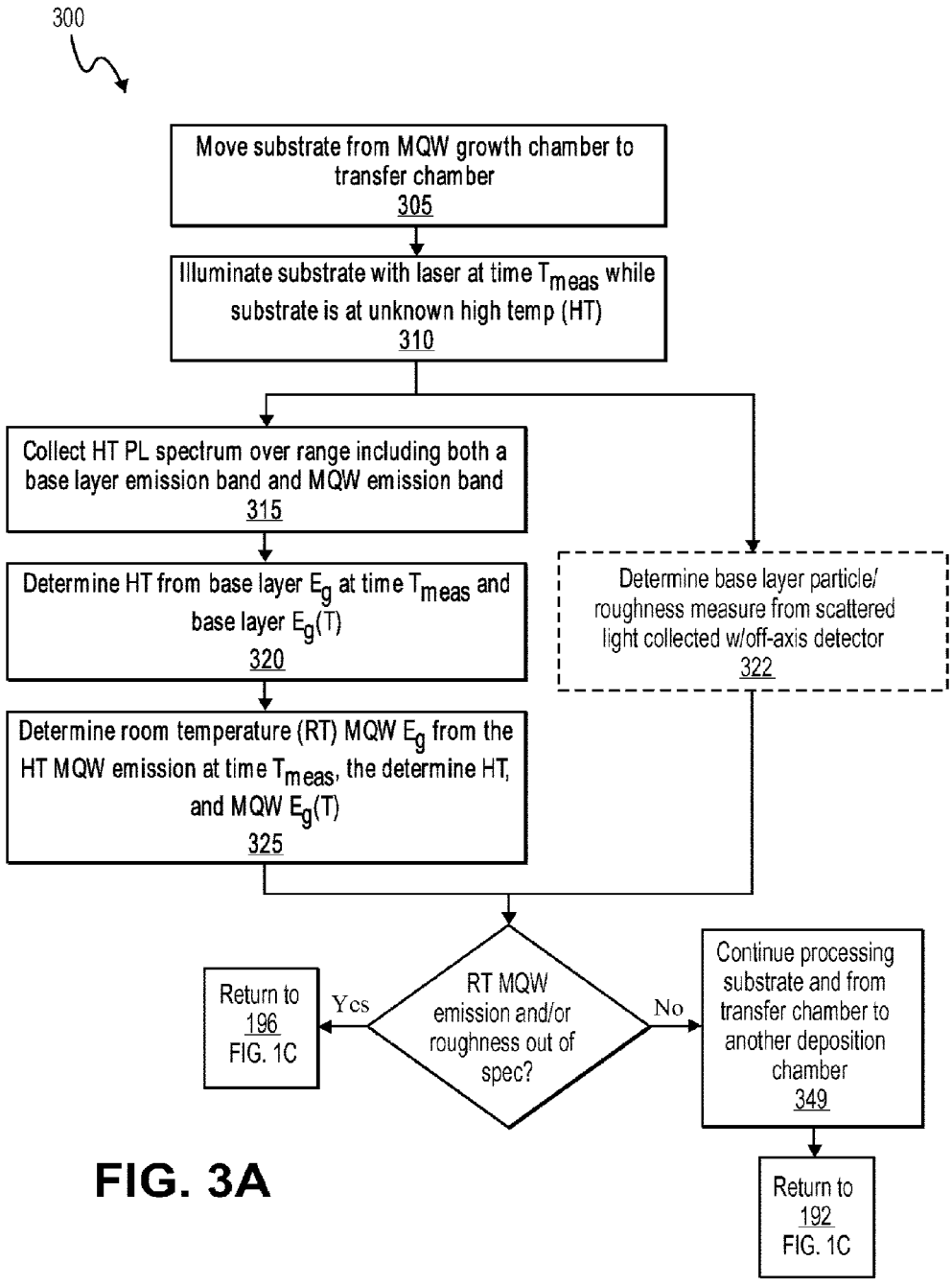
300
Move substrate from MQW growth chamber to transfer chamber
305
Illuminate substrate with laser at time T_{meas} while substrate is at unknown high temp (HT)
310
Collect HT PL spectrum over range including both a base layer emission band and MQW emission band
315
Determine HT from base layer E_g at time T_{meas} and base layer $E_g(T)$
320
Determine room temperature (RT) MQW E_g from the HT MQW emission at time T_{meas}, the determine HT, and MQW $E_g(T)$
325
Determine base layer particle/ roughness measure from scattered light collected w/off-axis detector
322
RT MQW emission and/or roughness out of spec?
Yes
Return to 196 FIG. 1C
No
Continue processing substrate and from transfer chamber to another deposition chamber
349
Return to 192 FIG. 1C

FIG. 3A

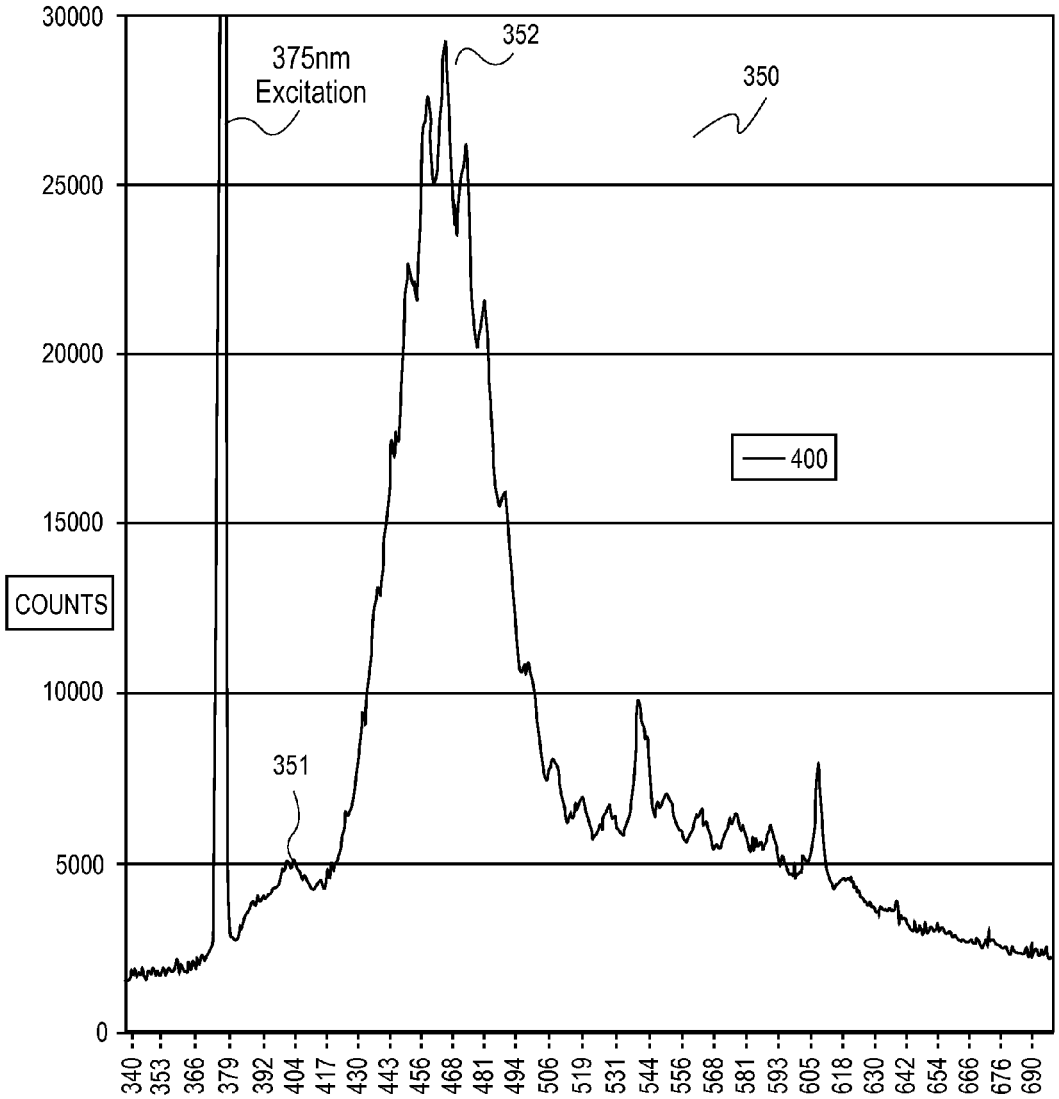
30000
25000
20000
15000
10000
5000
0
COUNTS
375nm
Excitation
352
350
400
351
340
353
366
379
392
404
417
430
443
456
468
481
494
506
519
531
544
556
568
581
593
605
618
630
642
654
666
676
690

FIG. 3B

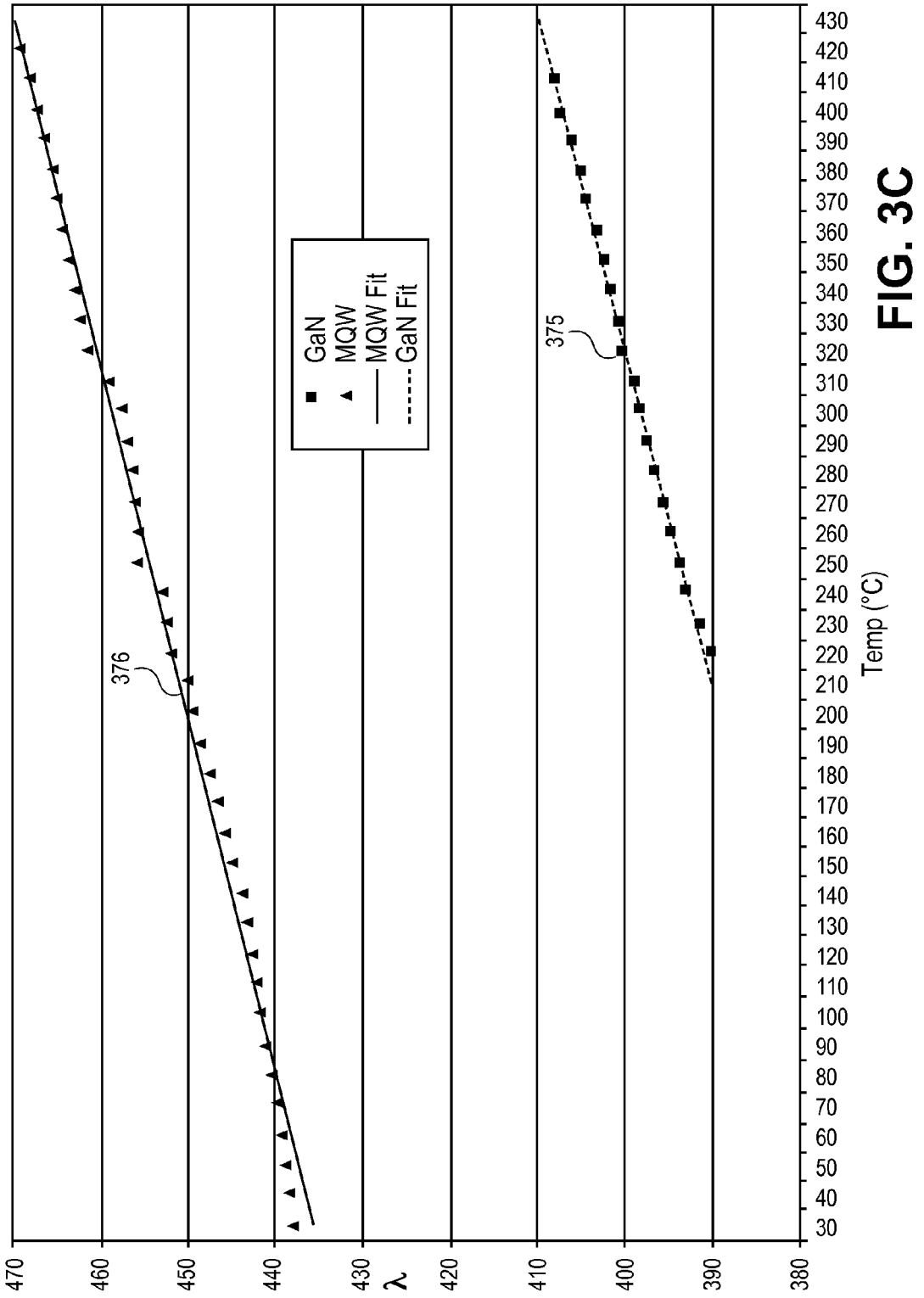
GaN
MQW
MQW Fit
GaN Fit
376
375
λ
Temp (°C)
470
460
450
440
430
420
410
400
390
380
430
420
410
400
390
380
370
360
350
340
330
320
310
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30

FIG. 3C

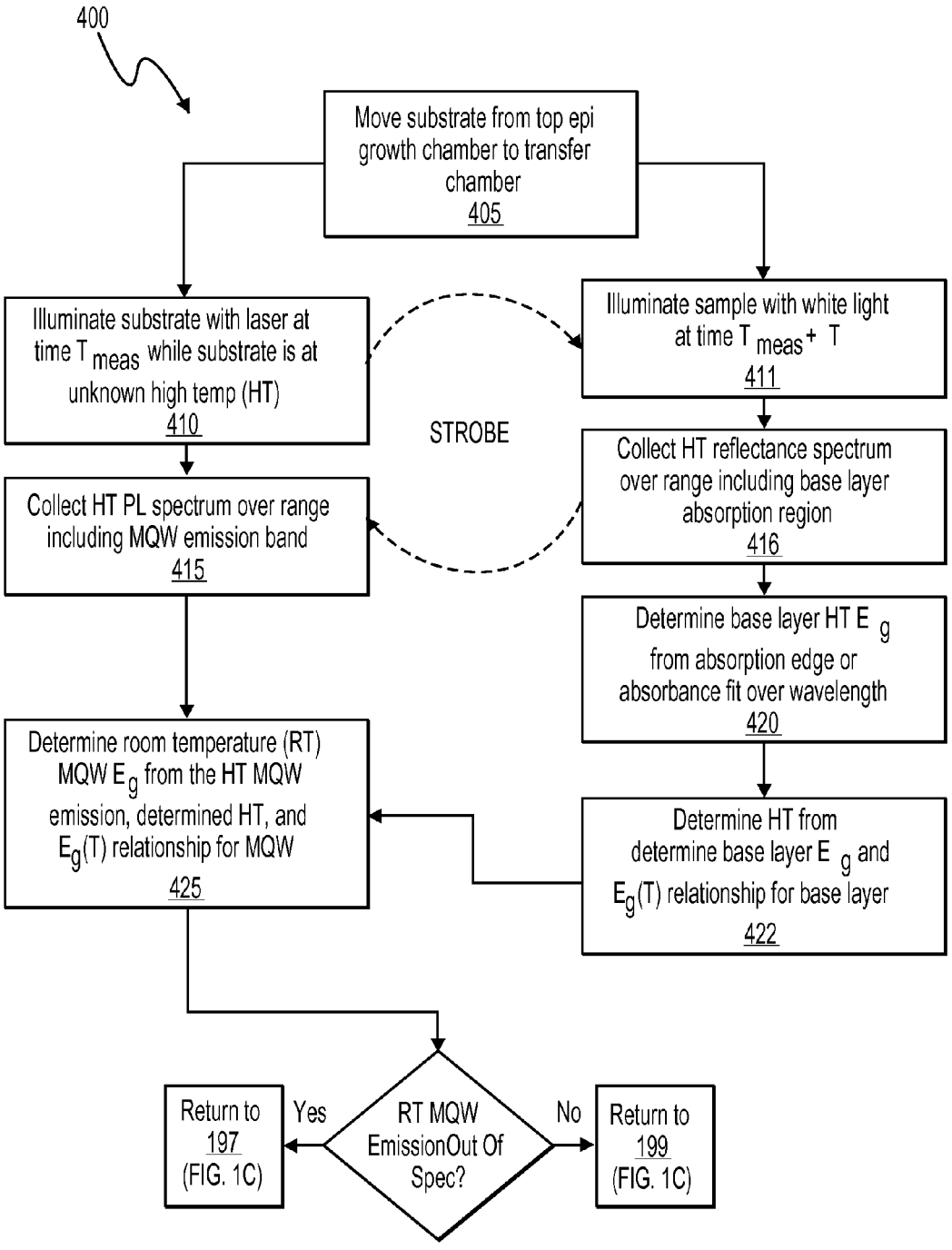
400
Move substrate from top epi growth chamber to transfer chamber 405
Illuminate substrate with laser at time T meas while substrate is at unknown high temp (HT) 410
STROBE
Illuminate sample with white light at time T meas + T 411
Collect HT reflectance spectrum over range including base layer absorption region 416
Collect HT PL spectrum over range including MQW emission band 415
Determine base layer HT E g from absorption edge or absorbance fit over wavelength 420
Determine room temperature (RT) MQW E g from the HT MQW emission, determined HT, and Eg(T) relationship for MQW 425
Determine HT from determine base layer E g and Eg(T) relationship for base layer 422
Return to 197 (FIG. 1C)
Yes
RT MQW EmissionOut Of Spec?
No
Return to 199 (FIG. 1C)

FIG. 4A

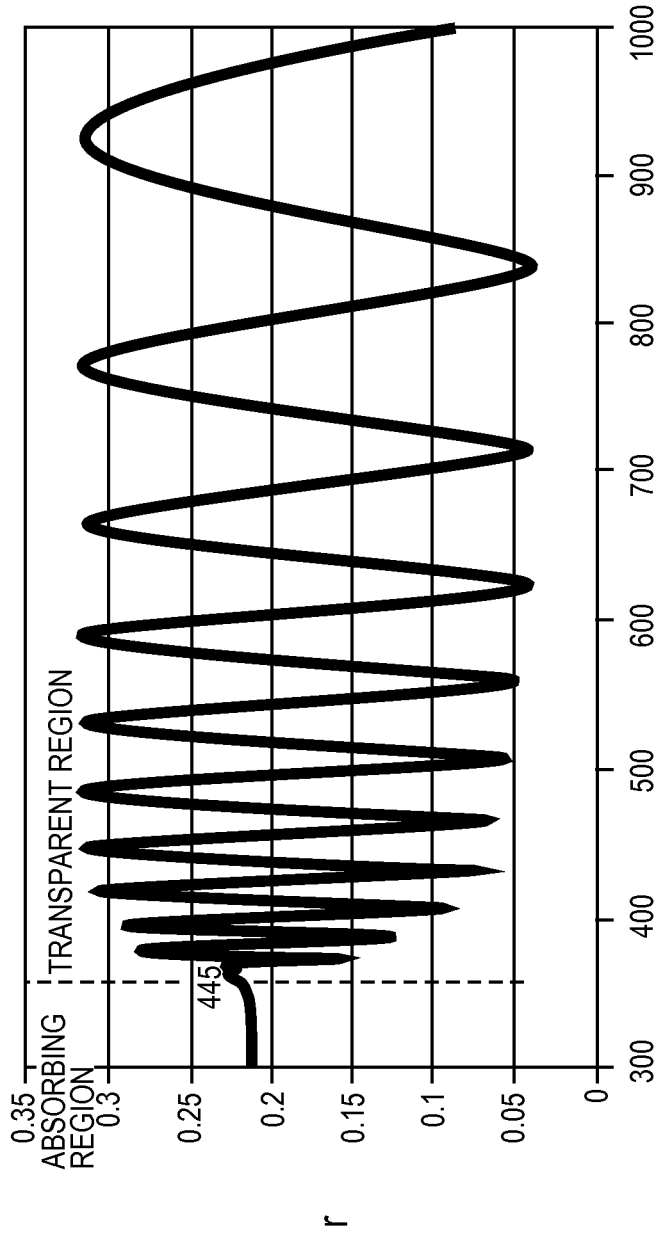
ABSORBING REGION
TRANSPARENT REGION
445
r
λ
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
300
400
500
600
700
800
900
1000

FIG. 4B

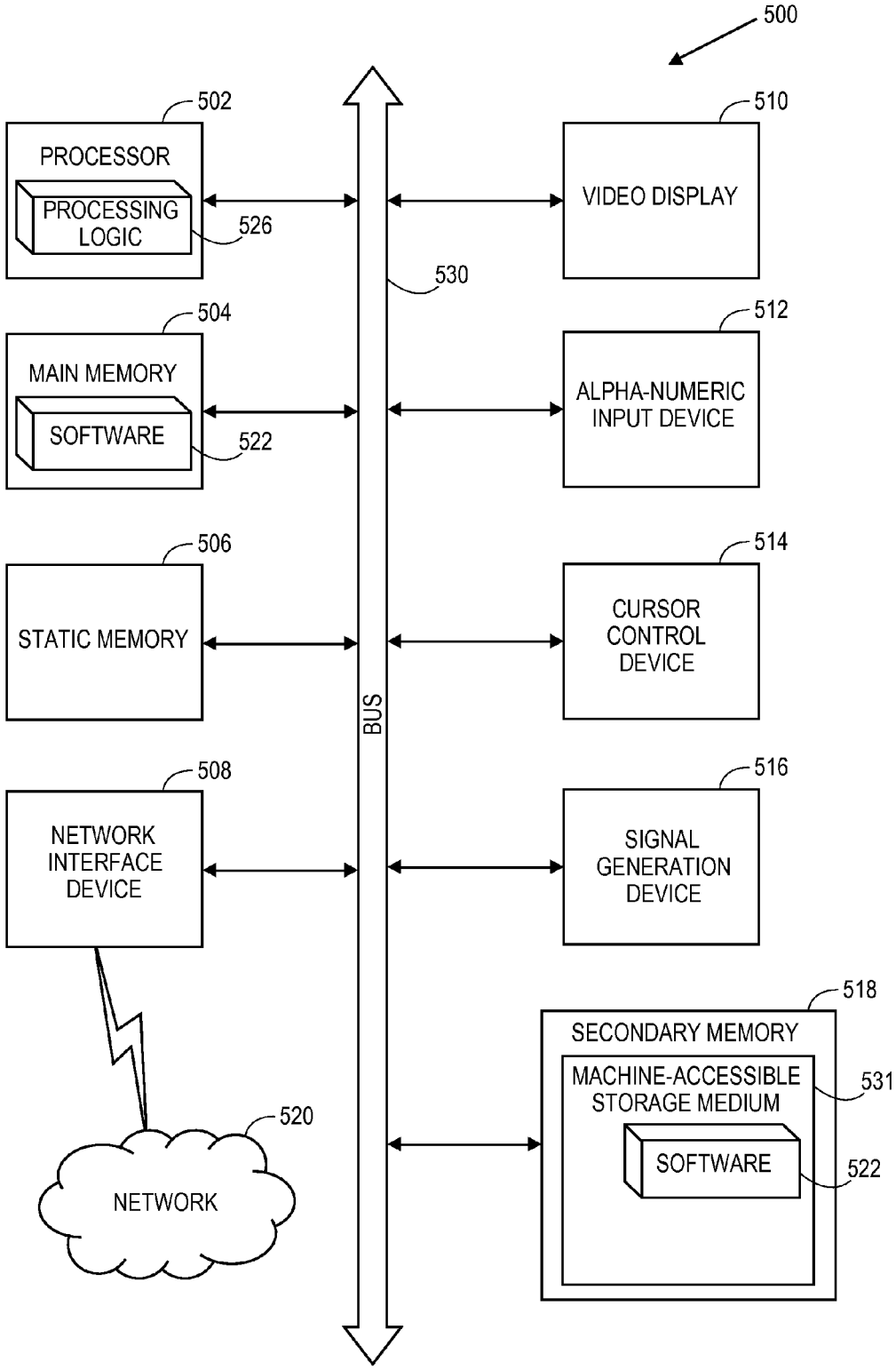
500
502
PROCESSOR
PROCESSING LOGIC
526
504
MAIN MEMORY
SOFTWARE
522
506
STATIC MEMORY
508
NETWORK INTERFACE DEVICE
520
NETWORK
530
BUS
510
VIDEO DISPLAY
512
ALPHA-NUMERIC INPUT DEVICE
514
CURSOR CONTROL DEVICE
516
SIGNAL GENERATION DEVICE
518
SECONDARY MEMORY
MACHINE-ACCESSIBLE STORAGE MEDIUM
531
SOFTWARE
522

FIG. 5

TRANSFER CHAMBER METROLOGY FOR IMPROVED DEVICE YIELD

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 61/382,835 filed on Sep. 14, 2010, entitled "TRANSFER CHAMBER METROLOGY FOR IMPROVED DEVICE YIELD," the entire contents of which are hereby incorporated by reference in its entirety for all purposes.

BACKGROUND

1. Field

Embodiments of the present invention pertain to the field of automate process control, and in particular, to metrology and control of epitaxially grown material layers in a light emitting diode (LED) film stack.

2. Description of Related Art

Group III-V materials are playing an ever increasing role in the semiconductor device and related, e.g. light-emitting diode (LED), industries. While devices such as LEDs employing multiple quantum well (MQW) structures epitaxially grown on a substrate are a promising technology, epitaxial growth of such structures is difficult because of the very thin material layers formed and the dependence of device properties (e.g., emission wavelength) on the material and physical characteristics of those layers.

The material and/or physical characteristics of an MQW structure are dependent on the growth environment within an epitaxy chamber. Post-manufacture metrology of an LED material stack provides a manufacturing control point which too far downstream to avoid significant yield loss in the event one of the epitaxial growth processes forming the LED stack deviating out of specification. In-situ metrology of an LED material stack however is prohibitive because of the epitaxy chamber and environment therein obscures observation of material properties.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings, in which:

FIG. **1**A illustrates a cross-sectional view of a GaN-based LED film stack which is grown using the growth temperature control method depicted in FIG. **1**A, in accordance with an embodiment of the present invention;

FIG. **1**B is a block diagram illustrating a plan view of a multi-chambered cluster tool including transfer chamber metrology, in accordance with an embodiment of the present invention;

FIG. **1**C is a flow diagram illustrating a method for epitaxial growth control, in accordance with an embodiment of the present invention;

FIG. **2** is a flow diagram illustrating a method for measuring a thickness, particle and/or roughness, and resistivity of a semiconductor base layer in a transfer chamber of the cluster tool depicted in FIG. **1**B, in accordance with an embodiment of the present invention;

FIG. **3**A is a flow diagram illustrating a method for measuring a band gap energy of a group III-V film on a substrate disposed in a chamber of the cluster tool depicted in FIG. **1**B, in accordance with an embodiment of the present invention;

FIG. **3**B is a PL spectra for the GaN-based LED film stack of FIG. **1**A as excited by a 375 nm collimated laser light source while the substrate is at a high temperature, in accordance with an embodiment of the present invention;

FIG. **3**C are graphs of band gap energy of the group III-V film and of the semiconductor base layer as a function of temperature, in accordance with an embodiment of the present invention;

FIG. **4**A is a flow diagram illustrating a method for measuring a band gap energy of a group III-V film on a substrate disposed in a chamber of the cluster tool depicted in FIG. **1**B, in accordance with an embodiment of the present invention

FIG. **4**B is a graph of a white light reflectance spectrum of a semiconductor base layer measured in a chamber of the cluster tool depicted in FIG. **1**B, in accordance with an embodiment of the present invention; and

FIG. **5** is a schematic of a computer system, in accordance with an embodiment of the present invention.

SUMMARY

Light-emitting diodes (LEDs) and other electronic devices may be fabricated from layers of group III-V films. Exemplary embodiments of the present invention relate to the controlling the growth of group III-V and group III-nitride films, such as, but not limited to gallium nitride (GaN) films.

Disclosed herein are apparatuses and method for control of epitaxial growth parameters. In particular embodiments, growth of an LED film stack comprises three separate growth operations, after each of which the substrate passes through a transfer chamber of a multi-chamber cluster tool. Metrology is performed as the substrate passes through the transfer chamber. Embodiments include PL measurement of a group III-V film grown in a first chamber while a substrate is at an elevated (high) temperature. In other embodiments, a film thickness measurement, a contactless resistivity measurement, and a particle and/or roughness measure is performed after growth of a semiconductor base layer over which the group III-V film is grown. Control of the semiconductor growth process is performed by a system controller which modifies growth parameters based on the transfer chamber metrology.

For embodiments, the substrate is at an elevated temperature when measured and one or more of the measurements performed in the transfer chamber are temperature corrected to room temperature by estimating the elevated temperature based on emission from a base layer having a known composition disposed below the group III-V film. In other embodiments, temperature correction is based on an absorbance band edge of the base layer determined from collected white light reflectance spectra.

DETAILED DESCRIPTION

In the following description, numerous details are set forth. It will be apparent, however, to one skilled in the art, that the present invention may be practiced without these specific details. In some instances, well-known methods and devices are shown in block diagram form, rather than in detail, to avoid obscuring the present invention. Reference throughout this specification to "an embodiment" means that a particular feature, structure, function, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. Thus, the appearances of the phrase "in an embodiment" in various places throughout this specification are not necessarily referring to the same embodiment of the invention. Furthermore, the particular

features, structures, functions, or characteristics may be combined in any suitable manner in one or more embodiments. For example, a first embodiment may be combined with a second embodiment anywhere the two embodiments are not mutually exclusive.

Disclosed herein are apparatuses and methods for control of epitaxial growth parameters. While a vast range of epitaxial films of differing composition and thicknesses may be grown employing the techniques described herein, light-emitting diodes (LEDs) and devices having multiple quantum well (MQW) structures fabricated from layers of group III-V films are particularly well-suited for certain of the apparatuses and methods. As such, exemplary embodiments of the present invention are described in the context of group III-V and group III-nitride films, such as, but not limited to gallium nitride (GaN) films and MQW structures grown thereon. While the exemplary embodiments serve to illustrate embodiments considered particularly advantageous, the techniques and system described may be readily applied to other material systems and devices.

FIG. **1**A illustrates a cross-sectional view of a GaN-based LED film stack which is grown in accordance with an embodiment of the present invention. In FIG. **1**A, an LED stack **105** is formed on a substrate **157**. In one implementation, the substrate **157** is single crystalline sapphire. Other embodiments contemplated include the use of substrates other than sapphire substrates, such as silicon (Si), germanium (Ge), silicon carbide (SiC), gallium arsenide (GaAs), zinc oxide (ZnO), lithium aluminum oxide (γ-$LiAlO_2$).

Disposed upon the substrate **157**, are one or more semiconductor base layers **158** which may include a III-V material such as any number of group III-nitride based materials, including, but not limited to, GaN, InGaN, AlGaN. The base layer **158** may include a buffer layer which provides either a polar GaN starting material (i.e., the largest area surface is nominally an (h k l) plane wherein h=k=0, and l is non-zero), a non-polar GaN starting material (i.e., the largest area surface oriented at an angle ranging from about 80-100 degrees from the polar orientation described above towards an (h k l) plane wherein l=0, and at least one of h and k is non-zero), or a semi-polar GaN starting material (i.e., the largest area surface oriented at an angle ranging from about >0 to 80 degrees or 110-179 degrees from the polar orientation described above towards an (h k l) plane wherein l=0, and at least one of h and k is non-zero). One or more bottom n-type epitaxial layers are further included in the base layer **158** to facilitate a bottom contact. The bottom n-type epitaxial layers may be any doped or undoped n-type group III-nitride based materials, such as, but not limited to, GaN, InGaN, AlGaN.

As further depicted in FIG. **1**A, a multiple quantum well (MQW) structure **162** is disposed over an n-type epitaxial layer of the base layer **158**. The MQW structure **162** may be any known in the art to provide a particular emission wavelength at an operating temperature of the LED (e.g., room temperature). In a certain embodiments, the MQW structure **162** includes a group III-V film, which for example, may have a wide range of indium (In) content within GaN. Depending on the desired wavelength(s), the MQW structure **162** may have between about a 10% to over 40% of mole fraction indium as a function of growth temperature, ratio of indium to gallium precursor, etc. It should also be appreciated that any of the MQW structures described herein may also take the form of single quantum wells (SQW) or double hetereostructures that are characterized by greater thicknesses than a QW. The base layer **158** and MQW structure **162** may be grown in a metalorganic chemical vapor deposition (MOCVD) chamber or a hydride/halide vapor phase epitaxy (HVPE) chamber, or any deposition chamber known in the art. Any growth techniques known in the art may be utilized with such chambers.

One or more p-type epitaxial layers **163** are disposed over the bottom MQW structure **162**. The p-type epitaxial layers **163** may include one or more layers of differing material composition forming a top of the LED stack **105**. In the exemplary embodiment, the p-type epitaxial layers **163** include both p-type GaN and p-type AlGaN layers doped with Mg. In other embodiments only one of these, such as p-type GaN are utilized. Other materials known in the art to be applicable to p-type contact layers for GaN systems may also be utilized. The thicknesses of the p-type epitaxial layers **163** may also vary within the limits known in the art. The p-type epitaxial layers **163** may also be gown in an MOCVD or HVPE epitaxy chamber. Incorporation of Mg during the growth of the p-type epitaxial layers **163** may be by way of introduction of Cp_2 Mg to the epitaxy chamber, for example.

Additional layers (not depicted), such as, tunneling layers, n-type current spreading layers and further MQW structures (e.g., for stacked diode embodiments) may be disposed on the LED stack **105** in substantially the same manner described for the layers **158**, **162** and **163** or in any manner known in the art. Following the growth of the LED stack **105**, conventional patterning and etching techniques expose regions of the bottom n-type GaN layers (e.g., top surface of starting material **158**) and the p-type epitaxial layers **163**. Any contact metallization known in the art may then be applied to the exposed regions to form n-type electrode contact and p-type electrode contacts for the LED stack **105**. In exemplary embodiments, the n-type electrode is made of a metal stack, such as, but not limited to, Al/Au, Ti/Al/Ni/Au, Al/Pt/Au, or Ti/Al/Pt/Au. Exemplary p-type electrode embodiments include Ni/Au or Pd/Au. For either n-type or p-type contacts, a transparent conductor, such as Indium Tin Oxide (ITO), or others known in the art, may also be utilized.

FIG. **1**B is a block diagram illustrating a plan view of a multi-chambered cluster tool **110** including transfer chamber metrology, in accordance with an embodiment of the present invention. The cluster tool **110** is a modular system comprising multiple process chambers **102** A,B,C that perform various processing steps that are used to form an electronic device stack, such as the LED stack **105**. The process chambers **102**A,B,C are each coupled to a transfer chamber **130**. As used herein, a transfer chamber is a chamber through which a substrate passes en route to a process chamber with no actual film growth or other material processing being performed in the transfer chamber. In the exemplary embodiment, the transfer chamber **130** is between the process chambers **102** A,B,C and load locks (not depicted) through which substrates may be loaded and unloaded, to and from, the cluster tool **110**. In embodiments, the transfer chamber **130** has an internal volume which houses a robot (not depicted) that is adapted to transfer substrates **133**. The robot supports the substrate carrier **114** which carries one or more substrates **133**, and the substrate carrier **114** is transferred between the process chambers **102** A,B,C and batch load locks. It should be noted however, that not all embodiments of a transfer chamber house a robot. A load-lock may also function as a cool-down chamber for the substrates **133** and/or carrier **114**. The transfer chamber **130** includes a lid (not depicted) and the internal volume may be maintained at a vacuum condition. In a specific embodiment, the internal volume of the transfer chamber **130** is filled with nitrogen gas and maintained at a pressure of about 20 Torr to about 200 Torr.

In one aspect of the invention, the cluster tool **110** includes a system controller **161** which is adapted to carry out various

substrate processing methods and sequences and analyze the processing results as observed by transfer chamber metrology. The multi-chambered cluster tool **110** may be any platform known in the art that is capable of adaptively controlling a plurality of process modules simultaneously. Exemplary embodiments include an Opus™ AdvantEdge™ system or a Centura™ system, both commercially available from Applied Materials, Inc. of Santa Clara, Calif.

In the exemplary embodiment shown in FIG. **1**B, three process chambers **102**A, **102**B and **102**C are coupled to the transfer chamber **130**, although six or more such process chambers may be coupled to the transfer chamber **130**. In the depicted embodiment each of the three process chambers **102**A,B,C are configured to perform epitaxial growths of semiconductor films. Each of the deposition chambers may be of any type, such as, but not limited to metal organic chemical vapor deposition (MOCVD) and HVPE chambers. In other embodiments, one or more of the process chambers **102**A,B,C is a rapid thermal processing (RTP) chamber for substrate annealing, an epitaxial (EPI) deposition chamber, a chemical vapor deposition (CVD) chamber that is adapted to deposit a metal or dielectric layer, an etch chamber, or a sputtering (PVD) chamber. For the exemplary embodiment, the process chambers **102**A,B,C perform particular group III-V growth operations described elsewhere herein on a substrate **133** or batch of substrates disposed on a carrier **114**.

Embodiments described herein which utilize an intra-LED stack growth transfer of the substrate between two epitaxy chambers may be performed using the multi-chambered system depicted in FIG. **1**B with a metrology operation occurring at least once as the substrate **133** and/or carrier **114** is displaced through the transfer chamber **130** en route between two process chambers or en route to a load lock after processing is completed or terminated.

Fitted to the transfer chamber **130** are one or more metrology tools adapted to measure one or more of thickness, particle and/or surface roughness assessments, temperature, band gap, or resistivity of a deposited film on the surface of the substrate. Optical hardware to perform techniques including ellipsometry, reflectometry, or X-ray photoelectron spectroscopy (XPS) may be fitted to the transfer chamber **130** to perform such measurements between runs of the process chambers **102**A,B,C. Similarly, hardware to perform any of X-ray diffraction (XRD), X-ray fluorescence (XRF), X-ray reflectivity (XRR), Auger electron spectrometry (AES), transmission electron microscopy (TEM), atomic force microscopy (AFM), UV Raman spectroscopy, mass spectrometry (e.g., residual gas analyzer), energy dispersive spectroscopy (EDSITEM), photoluminescence (PL) spectroscopy, electroluminescense (EL) spectroscopy (also referred to as flash LED spectroscopy may also be fitted to the transfer chamber **130**.

Because many of the observations made by the metrology techniques described herein have a dependence on temperature and because the substrate **133** while in the cluster tool **110** will be at a temperature elevated above room temperature (having been removed from a deposition chamber which typically operates at 400° C. or more), equipment to perform contactless temperature measurements may also be fitted to the transfer chamber **130**. For example, in embodiments a pyrometer and/or optical hardware to perform a technique known as band edge thermometry may be fitted to the transfer chamber **130** or another chamber of the cluster tool **110** through which the substrate **133** is made to pass en route between process chambers.

In the exemplary embodiment illustrated in FIG. **1**B, the transfer chamber **130** includes a PL apparatus. As shown, a laser light source **140** is coupled to the transfer chamber **130** to illuminate an area of a grown film while the substrate **133** is disposed in the transfer chamber **130**. In an embodiment, the excitation laser is disposed outside the transfer chamber **130** to provide excitation through a quartz or sapphire window disposed in a lid or other wall of the transfer chamber **130**. The laser light source **140** may be positioned outside of the transfer chamber **130** to illuminate an area of the grown film with incident light. The laser light source **140** may be utilized for both photoluminescence spectroscopy (PL) and a particle/surface roughness assessment. Generally the laser light source **140** may be of any type utilized in the art for PL. In the exemplary embodiment, the laser light source **140** is a cw laser diode which emits at a wavelength absorbed by the semiconductor base layer **158** when the base layer is at the elevated temperatures expected when disposed in the cluster tool **110**. For particular embodiments where the base layer **158** includes a GaN layer, the laser light source **140** emits at a wavelength below 405 nm. In particular embodiments, the laser light source **140** emits at a wavelength of at least 360 nm. In a preferred embodiment, the laser light source **140** emits at a wavelength of approximately 375 nm.

Because the substrate **133** is at an elevated temperature and is cooling while it is transferred between process chambers, the substrate **133** can be expected to be warped to various degrees over time. For this reason, the laser light is preferably not a focused beam, but rather a collimated beam having spot size of at least 25 μm and preferably between 50 and 2000 μm. Given collimated beams have a lower energy density than focused beams, it is important that the collimated beam is pumped to have sufficient power to illuminate the spot size at a sufficient energy density to produce an emission signal which can be collected over the noise attributable to the elevated substrate temperature. For the exemplary embodiment having a laser light source **140** emitting at a wavelength of 375 nm and an average power of 15 mW has been found to provide good results. However, the average power may be anywhere between 2 mW and 200 mW, or greater depending on the base layer composition, substrate temperature, and spot size.

As further illustrated in FIG. **1**B, a collection fiber **141** penetrates into the transfer chamber **130**, for example through the lid. In an embodiment, the collection fiber **141** is a large-core fiber to collect the photoluminescence in an on-axis position, normal to a top surface of the epitaxially grown films being measured. Alternatively, collection optics may be disposed exterior to the transfer chamber **130** to image the PL, but alignment is then made more difficult. For some embodiments where the collection fiber **141** penetrates the transfer chamber **130**, all or a subset of the plurality of substrates **133** on the carrier **114** are measured, or mapped by flexing ends of the fibers within the transfer chamber **130**. In alternative embodiments, where the collection fiber **141** is fixed or where the collection optics are disposed outside of the transfer chamber **130**, motion of the robot arm permits mapping or measurement of representative substrates **133**.

The collection fiber **141** is further coupled to a spectrometer **143**. The spectrometer **143** may be any utilized in the art for the purpose of collecting PL emission spectra, such as one including a grating and a charged coupled device (CCD) array. In the exemplary embodiment, the spectrometer **143** records spectra over a wavelength range within which both the semiconductor base layer **158** and the MQW structure **162** absorb. More particularly, the spectrometer **143** records spectra over a wavelength range including PL emission bands from both the semiconductor base layer **158** and the MQW structure **162**. For the exemplary embodiment where the

semiconductor base layer **158** includes GaN and the MQW structure **165** includes InGaN, the spectrometer **143** records spectra between about 300 nm and 800 nm. The fiber coupled spectrometer **143** is disposed exterior the transfer chamber **130** and in the particular embodiment depicted in FIG. **1**B, the spectrometer **143** is utilized for collection of PL spectra as well as reflectance spectra in support of both the PL and reflectometry techniques described elsewhere herein.

In embodiments, the transfer chamber **130** further includes a reflectance apparatus. As shown in FIG. **1**B, the collection fiber **141** coupling the spectrometer **143** to the transfer chamber **130** may be one terminal of a bifurcated fiber having a second terminal coupled to a white light source **145**. The white light source may be of any type conventional in the art of reflectance measurement with the illumination fiber **144** penetrating the transfer chamber **130** to illuminate an area of a grown III-V film with light normal to the film's top surface. In the exemplary configuration depicted, the collection fiber **141** collects photoluminescence and reflected light normal to the film's surface in support of both PL and reflectometry techniques described elsewhere herein.

In an embodiment, the transfer chamber **130** includes an off-axis detector **148** to collect light scattered from the area of the III-V films illuminated by either the laser light source **140** or the white light source **145**. The off-axis detector **148** is to provide an assessment of surface roughness and/or a measure of particles on the surface of a grown III-V film. Components of the reflectometer may be utilized to assess the surface roughness/particles. For example, while the reflectance system illuminates and analyzes along a direction normal to the wafer, the same illumination source will generate scattered light in other directions from a rough surface. Therefore, the roughness may be evaluated by collecting scattered light in an off-normal direction. The off-axis detector **148** may be of any type utilized in the art for such purposes, such as a CCD array. In an alternative embodiment, a video camera typically utilized for monitoring robotic handling within the transfer chamber **130** may be utilized as the off-axis detector **148** and operated for the additional purpose of collecting surface roughness and/or particle data in the epitaxially grown film.

In an embodiment, the transfer chamber **130** further includes a resistance meter, for example to measure a sheet resistivity of a doped film grown on the substrate **133** by one of the process chambers **102**A,B,C. In a preferred embodiment, the resistance meter **150** is a contactless resistivity meter, such a microwave-reflectance system commercially available from Leighton, Inc. of Pennsylvania, U.S.A. Alternatively, a four point probe system utilizing spring loaded probes which contact the substrate **133** may also be fitted into the transfer chamber **130**.

As further depicted in FIG. **1**B, the cluster tool **110** includes an MQW band gap energy (E_g) estimator **153**. The MQW E_g estimator **153** may be implemented as software, hardware (e.g., as an ASIC or FPGA), or a combination of both. The MQW Eg estimator **153** is to access stored information, and to assess, from the metrology observations performed, the band gap of the MQW structure **162** (FIG. **1**A) grown in one or more of the process chambers **102** A,B,C. Generally, the stored information accessed by the MQW E_g estimator **153** may be in the form of a database, a look-up table (LUT), or a mathematical equation representing a theoretically or empirically modeled system. In a particular embodiment, the stored information includes information **154** containing band gap energy of at least one MQW structure determinable as a function of temperature, ($E_{g,\,MQW}(T)$) as well as information **155** containing band gap energy of at least one semiconductor base layer composition (e.g., GaN) determinable as a function of temperature, ($E_{g,\,base\ layer}(T)$). In further embodiments, the MQW band gap energy (E_g) estimator **153** also includes an absorbance analyzer **156** to determine a temperature from a reflectance spectrum, for example utilizing a band edge technique as further described elsewhere herein.

FIG. **1**C is a flow diagram illustrating a method **180** for epitaxial growth control, in accordance with an embodiment of the present invention in which a compound semiconductor structure, such as the LED stack **105** depicted in FIG. **1**A, is fabricated using the processing system shown in FIG. **1**B. The method **180** begins at operation **181** with selecting a new substrate for a split-chamber growth process. Generally, a split-chamber growth process entails a transfer between deposition chambers **102**A,B,C during growth of a device material stack. For example, in reference to the LED stack **105**, a split-chamber grow process includes three distinct growth segments: 1) growth of the n-type GaN base layer **158** in a first chamber, 2) growth of InGaN MQW structure **162** in a second chamber, and 3) growth of p-type AlGaN layer **163** in a third chamber. As shown in FIG. **1**C, transfer chamber metrology may be applied during the breaks in epitaxial growth, for example to check whether the grown layers are of the proper structure/composition/doping/thickness/etc. During the split-chamber growth process, metrology may be performed in an automated fashion, incorporated as part of a transfer sequence between process chambers **102** A,B,C and performed under the vacuum/inert-environment of the transfer chamber **130**. With a substrate **133** in a first process chamber (e.g., deposition chamber **102**A), a semiconductor base layer (e.g., GaN base layer **158**) is grown at operation **185**. Generally, base layer growth is performed at an elevated temperature, for example exceeding 400° C.

Following growth of the semiconductor base layer, the substrate is transferred out of the first deposition chamber and into the transfer chamber **130**. At operation **186**, transfer chamber metrology is performed. Any of the measurement techniques described previously, such as, but not limited to, reflectometry, PL, resistivity, or surface roughness measurements may be performed at operation **186**. In a particular embodiment, at least one of reflectance apparatus, resistance meter **150**, and off-axis detector **148** are used to determine a film thickness, resistivity or surface roughness for the base layer grown in the first deposition chamber. In a particular embodiment, a transfer chamber metrology method **200**, as further illustrated in FIG. **2**, is performed at operation **186** to provide base layer growth process control based at least upon a base layer resistivity measurement.

Referring to FIG. **2**, the transfer chamber metrology method **200** includes at least a sheet resistance measurement and may further include a surface roughness assessment, and a film thickness measurement of the base layer **158** grown in the deposition chamber **102**A. At operation **205**, the substrate **133** is moved from the base layer growth chamber to the transfer chamber **130**. At operation **210**, the substrate **133** is illuminated with white light. At operation **215**, a film thickness of the base layer **158** is determined from reflectance normal to the film surface collected with the spectrometer **143**. At operation **220**, a particle and/or surface roughness assessment may be made concurrently with scattered white light collected with the off-axis detector **148**. At operation **225**, resistivity of the base layer **158** is determined with a non-contact resistance measurement at operation **225**. Measured values are then compared with thresholds to determine if the measured film is outside of material specifications.

Where the transfer chamber metrology operation **186** indicates the processed substrate(s) **133** to be within specifica-

tion, processing is continued at operation **249** with the substrate transferred into a second deposition chamber (e.g., deposition chamber **102**B) where the transfer chamber metrology method **200** returns to operation **188** of FIG. **1**C for growth of another III-V film over the base layer **158** (e.g., MQW structure **162**).

Where the transfer chamber metrology operation **186** indicates the processed substrate(s) **133** to be outside specification, the transfer chamber metrology method **200** returns to operation **195** (FIG. **1**C) where a process parameter of the first deposition chamber is updated to modify the process by which the base layer is grown on a subsequently processed substrate. For example, the system controller **161** may modify a growth duration for the semiconductor base layer of a subsequently processed substrate based on a thickness of the semiconductor base layer determined from the reflectance spectrum collected at operation **215**. In other embodiments, the system controller **161** modifies a precursor partial pressure or growth duration for the semiconductor base layer of a subsequently processed substrate based on the sheet resistivity of the semiconductor base layer determined at operation **225**. As such, a growth process control effort is exerted based on the transfer chamber metrology performed at operation **186**. The substrate measured at operation **186** is further dispositioned at operation **195**. If the substrate has been rendered unusable, further processing of the processed substrate(s) may be terminated with the carrier **114** placed back in the load lock to be unloaded for scrap or rework. Alternatively, further processing of the substrate **133** may proceed with perhaps reduced yield expected.

Returning to FIG. **1**C, at operation **188**, the group III-V film is grown and the processed substrate(s) again removed to the transfer chamber **130**. Generally, the growth operation **188** is performed at an elevated temperature, for example above 400° C. At operation **190**, transfer chamber metrology is again performed, this time to characterize the III-V film grown in the second deposition chamber. Any of the measurement techniques described previously, such as, but not limited to, PL reflectometry, resistivity or surface roughness measurements may be performed at operation **190**, depending on the type of III-V film grown at operation **188**. In the exemplary embodiment where the MQW structure **162** is grown at operation **188**, the transfer chamber metrology method **300** depicted in FIG. **3**A is performed at operation **190** to provide MQW growth process control based at least upon a room temperature MQW E_g estimate. In an alternative embodiment where the MQW structure **162** is grown at operation **188**, the transfer chamber metrology method **400** depicted in FIG. **4**A is performed at operation **190** to provide MQW growth process control based at least upon a room temperature MQW E_g estimate. In still other embodiments, both the transfer chamber metrology methods **300** and **400** are performed at operation **190** to provide MQW growth process control based at least upon a room temperature MQW E_g estimate.

Referring to FIG. **3**A, the transfer chamber metrology method **300** includes at least a PL measurement and begins at operation **305** with moving the substrate(s) **133** from the MQW growth chamber to the transfer chamber **130**. While in the transfer chamber **130**, the substrate(s) **133** are illuminated by the laser light source **140** at time τ_{meas}. Because the MQW structure **162** was grown at an elevated temperature, the substrate **133** is cooling from the process temperature while in the transfer chamber **130** and will be at an unknown high temperature (HT) at time τ_{meas}. At operation **315**, a PL spectrum is collected by the spectrometer **143** over a range including emission bands of both the base layer **158** and MQW structure **162**.

An exemplary PL spectrum **350** for an embodiment where the base layer **158** is GaN and the MQW structure **162** includes InGaN is depicted in FIG. **3**B. The PL spectrum **350** is in response to excitation by a 375 nm collimated laser light source having an average power of 15 mW. As depicted, with the substrate temperature elevated to the high temperature, the GaN base layer **158** and MQW structure **162** is photoluminescent with a base layer emission band **351** and a MQW emission band **352**.

At operation **320**, the substrate temperature at time τ_{meas} is determined from the band gap energy (E_g) observed for the base layer **158**. Referring to FIG. **1**B, the MQW Eg estimator **153** is to access the base layer $E_g(T)$ information **155** given that the base layer composition is a well-controlled parameter. For example, where the base layer **158** includes GaN, the base layer $E_g(T)$ information **155** contains band gap values of GaN as a function of temperature which can be described by Varshni's equation:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

where $E_g(0)$, α and β are material constants. Alternatively, the base layer $E_g(T)$ information **155** may be a fitted model derived for the particular base layer semiconductor. FIG. **3**C depicts a graph **375** of measured band gap energy of a GaN base layer **158** as a function of temperature and a modeled fit of the measured energies which may be used to estimate the substrate temperature in accordance with an embodiment of the present invention. Thus, in embodiments, at operation **320**, the substrate temperature at time τ_{meas} is estimated by first executing a standard peak detection algorithm to identify the peak of the base layer emission band **351**, and then determining the temperature associated with the peak emission energy on the GaN $E_g(T)$ graph **375**.

Returning to FIG. **3**A, at operation **325**, the room temperature MQW is determined based on the high temperature MQW emission band **352** and the substrate temperature estimated at operation **320**. In the exemplary embodiment, a standard peak detection routine is executed on the MQW emission band **352** and by applying Varshni's equation, for example, with the estimate temperature the room temperature MQW may be determined. Alternatively, a number of MQW band energies associated with a temperature (Eg(T)) information **154** contained in a LUT is accessed by the MQW E_g estimator **153** to determine the room temperature MQW. For example, FIG. **3**C further depicts a graph **376** of measured band gap energy of an MQW structure **162** as a function of temperature and a modeled fit of the measured energies, in accordance with an embodiment of the present invention. Where the MQW Eg(T) information **154** contains a plurality of datasets with each set forming a graph **376**, standard mathematical techniques may be performed to arrive at an estimate for the room temperature MQW E_g from a LUT containing a LUT of $E_g(T)$ information for different MQW structures.

The estimated room temperature MQW E_g, or an estimated LED emission wavelength, is then utilized as a MQW growth process control parameter in the method **180**. As such, the elevated temperature being sufficient to cause the base layer **158** to photoluminesce in addition to the MQW structure **162**, allows a single PL measurement at time τ_{meas} to generate a reference with which the high temperature PL measurement of the MQW structure **162** is corrected into a useful growth control parameter having very short feedback delay (e.g.,

much shorter than waiting for the substrate to cool to room temperature and then performing a room temperature PL measurement).

As further illustrated in FIG. **3**A, at operation **322**, a particle and/or surface roughness assessment may also be made concurrently with scattered laser light collected with the off-axis detector **148**. For embodiments where a patterned sapphire substrate is employed, the interface between the GaN base layer **158** and sapphire substrate **157** is intentionally rough. However, for embodiments where the laser light wavelength is sufficiently short to be absorbed by the GaN base layer **158** (e.g., 360-375 nm), the rough sapphire interface will not pose a problem for the surface roughness measurement when performed in the cluster tool **110** at the elevated temperature.

The estimated room temperature MQW E_g values and/or surface roughness values are compared with thresholds to determine if the measured III-V film is outside of material specifications. Where the transfer chamber metrology method **300** indicates the processed substrate(s) **133** to be within specification, processing is continued with the transfer chamber metrology method **300** returning to operation **192** of FIG. **1**C for growth of another III-V film (e.g., p-type top layer **163**). Where the transfer chamber metrology method **300** indicates the processed substrate(s) **133** to be outside specification, the transfer chamber metrology method **300** returns to operation **196** (FIG. **1**C) and a process parameter of the second deposition chamber is updated to modify the process by which the MQW structure **162** is to be grown on a subsequently processed substrate. For example in one embodiment the system controller **161** modifies a growth temperature for an MQW growth to be performed on a subsequently processed wafer in the second process chamber. As such, a growth control effort is exerted based on the transfer chamber metrology performed at operation **190**. The substrate(s) **133** measured at operation **190** are further dispositioned at operation **196**. If the substrate has been rendered unusable, further processing of the processed substrate(s) may be terminated with the carrier **114** placed back in the load lock for unloading. Alternatively, further processing may proceed with perhaps reduced yield expected.

Referring to FIG. **4**A, the transfer chamber metrology method **400** includes at least a PL measurement and begins at operation **405** with moving the substrate(s) **133** from the MQW growth chamber to the transfer chamber **130**. While in the transfer chamber **130**, the substrate(s) **133** is illuminated by the laser light source **140** at time τ_{meas}. Because the MQW structure **162** was grown at an elevated temperature, the substrate **133** is cooling from the process temperature while in the transfer chamber **130** and will be at an unknown high temperature (HT) at time τ_{meas}. At operation **415**, a high temperature PL spectrum is collected by the spectrometer **143** over a range including emission band of the MQW structure **162**. At operation **411**, the substrate is illuminated by the white light source **145** at time $\tau_{meas}+\Delta T$ and at operation **416** a high temperature reflectance spectrum is collected by the spectrometer **143** over a range including a semiconductor base layer absorption region. Generally, because each of the operations **410**, **415**, **411** and **416** can be performed in less than a few seconds, ΔT is very small and the two measurement spectrums collected at operation **415** and **416** may be assumed to be taken at the same time or the operations **410**, **415**, **411** and **416** strobed to generate a statistic of a plurality of spectrums (e.g., averaged HT PL spectrum and averaged HT reflectance spectrum), if desired.

At operation **420**, the base layer band gap energy E_g is determined from an absorption edge technique. For the absorption edge technique, when a semiconductor crystal is illuminated by polychromatic light, there is a sharp increase in photon absorption when the photon energy is greater than the semiconductor crystal band-gap energy. For example, FIG. **4**B depicts a graph of a white light reflectance spectrum of a 4 μm thick GaN semiconductor base layer **158** on a sapphire substrate, in accordance with an embodiment of the present invention. As shown, the absorption edge **445** separates the absorbing and transparent regions of the spectrum. The photon wavelength which corresponds to the band-gap energy is known as the band-edge wavelength and this wavelength is temperature dependent. Since the semiconductor crystal band-gap energy is inversely related to the lattice constant, the band-gap energy will decrease as the semiconductor crystal expands with increasing temperature and so the band-edge wavelength will increase. As such, the absorbance analyzer **156** can estimate the high temperature band gap energy E_g of the base layer at operation **420** based on the reflectivity spectrum collected at operation **415** using known spectral analysis techniques.

At operation **422**, the substrate temperature at time τ_{meas} (or $\tau_{meas}+\Delta T$) is determined from the band gap energy (E_g) determined for the base layer **158**. Referring to FIG. **1**B, the MQW E_g estimator **153** accesses the base layer $E_g(T)$ information **155** and because the base layer composition should be well-controlled an accurate estimate of the temperature may be made. For example, where the base layer **158** is GaN, the base layer $E_g(T)$ information **155** contains band gap values of GaN as a function of temperature (e.g., Varshni's equation) and the elevated (high) temperature can be estimated by the MQW estimator **153**. Alternatively, the base layer $E_g(T)$ information **155** may be a fitted model derived for the particular base layer semiconductor. Band gap energy graph of a GaN base layer **158** as a function of temperature and a modeled fit of the measured energies depicted in FIG. **3**B can also be utilized.

Returning to FIG. **4**A, at operation **425**, the room temperature MQW is determined based on the high temperature MQW emission and the substrate temperature estimated at operation **422**. In the exemplary embodiment, a standard peak detection routine is executed on the MQW emission band and by applying Varshni's equation, for example, with the estimated substrate temperature, the room temperature MQW E_g may be determined. Alternatively, a number of datasets, each having band energies associated with temperature (Eg(T)) for a particular MQW structure, contained in a LUT is accessed by the MQW E_g estimator **153** to determine the room temperature MQW E_g. For example, where the MQW Eg(T) information **154** contains a plurality of graphs like the graph **376** (FIG. **3**C), standard mathematical techniques may be performed to arrive at an estimate for the room temperature MQW E_g.

The estimated room temperature MQW E_g is then the basis for a MQW growth process control parameter in the method **180**. As such, the high temperature PL measurement of the MQW structure **162** is corrected into a useful growth control parameter having very short feedback delay (e.g., much shorter than waiting for the substrate to cool to room temperature and then performing a room temperature PL measurement). The estimated room temperature MQW E_g value is compared with thresholds to determine if the measured III-V film is outside of material specifications. Where the transfer chamber metrology method **400** indicates the processed substrate(s) **133** to be within specification, processing is continued with the transfer chamber metrology method **300** returning to operation **192** of FIG. **1**C for growth of another III-V film (e.g., p-type layer **163**). Where the transfer cham-

ber metrology method **400** indicates the processed substrate(s) **133** to be outside specification, the transfer chamber metrology method **400** returns to operation **196** (FIG. **1**C) where a process parameter of the second deposition chamber is updated to modify the process by which the MQW layer is to be grown on a subsequently processed substrate.

Returning to FIG. **1**C, at operation **192** another III-V film is grown on the substrate **133** in a third deposition chamber. In the exemplary embodiment, the p-type layer **163** is grown in the process chamber **102**C. Following the film growth, the substrate(s) **133** are transferred into a load lock where they may cool while other substrates are processed through the operations illustrated in FIG. **1**C. In an embodiment, following cooling to at or near room temperature, the substrate(s) **133** is moved back from the load lock into the transfer chamber and a final transfer chamber metrology is performed at operation **194**. Such in-situ room temperature metrology has the advantage of being faster than waiting for a full lot to complete processing on the cluster tool **110**, complete venting of the load lock, and complete loading a substrate onto a stand-alone metrology tool. Any of the transfer chamber measurement techniques described for the operations **186** and **188** may be performed at operation **194**. For example, in one embodiment, a room temperature PL measurement is performed to verify the room temperature MQW E_g is in agreement with the temperature corrected room temperature E_g estimate determined at operation **190** (e.g., via either method **300** or method **400**).

Where the processed substrate(s) **133** is outside specification at operation **194**, a process parameter of the second deposition chamber is updated at operation **197** to modify the process by which the MQW structure **162** is to be grown on a subsequently processed substrate. For example, in one embodiment the system controller **161** modifies a growth temperature for an MQW growth to be performed on a subsequently processed wafer in the second process chamber. As such, a control effort is exerted based on the transfer chamber metrology performed at operation **194**. The substrate(s) **133** measured at operation **194** are further dispositioned at operation **197**. If the substrate has been rendered unusable, further processing of the processed substrate(s) may be terminated with the carrier **114** placed back in the load lock for scrap or rework. Alternatively, the substrate may be placed back in the load lock and unloaded from the cluster tool **110** for subsequent patterning and/or metallization.

FIG. **5** illustrates a diagrammatic representation of a machine in the exemplary form of a computer system **500** which may be utilized as the system controller **161** to control one or more of the operations, process chambers or multi-chambered processing platforms described herein. In alternative embodiments, the machine may be connected (e.g., networked) to other machines in a Local Area Network (LAN), an intranet, an extranet, or the Internet. The machine may operate in the capacity of a server or a client machine in a client-server network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine may be a personal computer (PC) or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines (e.g., computers) that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein.

The exemplary computer system **500** includes a processor **502**, a main memory **504** (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM) or Rambus DRAM (RDRAM), etc.), a static memory **506** (e.g., flash memory, static random access memory (SRAM), etc.), and a secondary memory **518** (e.g., a data storage device), which communicate with each other via a bus **530**.

The processor **502** represents one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, the processor **502** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. The processor **502** may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. The processor **502** is configured to execute the processing logic **526** for performing the process operations discussed elsewhere herein.

The computer system **500** may further include a network interface device **508**. The computer system **500** also may include a video display unit **510** (e.g., a liquid crystal display (LCD) or a cathode ray tube (CRT)), an alphanumeric input device **512** (e.g., a keyboard), a cursor control device **514** (e.g., a mouse), and a signal generation device **516** (e.g., a speaker).

The secondary memory **518** may include a machine-accessible storage medium (or more specifically a computer-readable storage medium) **531** on which is stored one or more sets of instructions (e.g., software **522**) embodying any one or more of the methods or functions described herein. The software **522** may also reside, completely or at least partially, within the main memory **504** and/or within the processor **502** during execution thereof by the computer system **500**, the main memory **504** and the processor **502** also constituting machine-readable storage media.

The machine-accessible storage medium **531** may further be used to store a set of instructions for execution by a processing system and that cause the system to perform any one or more of the embodiments of the present invention. Embodiments of the present invention may further be provided as a computer program product, or software, that may include a machine-readable storage medium having stored thereon instructions, which may be used to program a computer system (or other electronic devices) to perform a process according to the present invention. A machine-readable storage medium includes any mechanism for storing information in a form readable by a machine (e.g., a computer). For example, a machine-readable (e.g., computer-readable) medium includes a machine (e.g., a computer) readable storage medium (e.g., read only memory ("ROM"), random access memory ("RAM"), magnetic disk storage media, optical storage media, flash memory devices, and other such non-transitory storage media known in the art.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent to those of skill in the art upon reading and understanding the above description. Although the present invention has been described with reference to specific exemplary embodiments, it will be recognized that the invention is not limited to the embodiments described, but can be practiced with modification and alteration. Accordingly, the specification and drawings are to be regarded in an illustrative sense rather than a restrictive sense.

What is claimed is:

1. A system for epitaxially growing a group III-V film on a substrate, the system comprising:

a deposition chamber to grow the group III-V film;

a transfer chamber coupled to the deposition chamber;

a laser light source coupled to the transfer chamber to illuminate an area of the group III-V film while the substrate is disposed in the transfer chamber at a first temperature, greater than room temperature;

a spectrometer coupled to the transfer chamber to collect an emission spectrum from the illuminated area;

and

a system controller coupled to the transfer chamber to determine an estimate of the first temperature based on the collected emission spectrum and to estimate a room temperature band gap energy of the group III-V film based on the estimated temperature.

2. The system of claim **1**, wherein the laser light source is to illuminate, through a window in the transfer chamber, the group III-V film with a collimated beam.

3. The system of claim **2**, wherein the laser light source is to illuminate a spot size on the group III-V film of between 25 and 2000 μm.

4. The system of claim **1**, wherein the laser light source is to illuminate the area of the III-V film with light incident to a top surface of the III-V film, and wherein the spectrometer is coupled to the transfer chamber via a collection fiber penetrating the transfer chamber to collect light normal to the top surface of the III-V film.

5. The system of claim **1**, wherein the laser light source emits at a wavelength which is absorbed by a semiconductor base layer disposed below the III-V film when at the first temperature.

6. The system of claim **5**, wherein the laser light source emits at a wavelength of at least 375 nm.

7. The system of claim **5**, wherein the spectrometer records spectra over a range including emission bands from both the semiconductor base layer and the III-V film.

8. The system of claim **7**, further comprising a database containing first information associating the band gap energy of the semiconductor base layer with temperature, and wherein the controller is to estimate the first temperature based on the semiconductor base layer emission band.

9. The system of claim **8**, further comprising a database containing second information associating the band gap energy of the group III-V film with temperature, and wherein the controller is to access the second information to determine the band gap energy of the group III-V film at room temperature.

10. The system of claim **1**, wherein the controller is to modify a growth temperature at which the group III-V film is to be grown on a subsequently processed substrate based on the determined band gap energy of the group III-V film.

11. The system of claim **1**, further comprising an off-axis detector to collect light reflected from the illuminated area of the III-V film.

12. The system of claim **1**, further comprising a white light source coupled to the transfer chamber to illuminate an area of the group III-V film while the substrate is disposed in the transfer chamber at the first temperature, and wherein the spectrometer is to collect a reflectance spectrum from the illuminated area over a wavelength range including wavelengths absorbed by a semiconductor base layer disposed below the III-V film.

13. The system of claim **12**, wherein the controller is to estimate the first temperature based on an absorbance edge determined from the reflectance spectrum.

14. The system of claim **13**, wherein the controller is to modify a duration of a semiconductor base layer growth performed on a subsequent substrate based on a thickness of the semiconductor base layer determined from the reflectance spectrum.

15. The system of claim **12**, wherein the white light source and spectrometer are coupled to the transfer chamber with a bifurcated optical fiber having a first end fitted into the transfer chamber, a second end fitted to the white light source and a third end fitted to the spectrometer.

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